“The Bright and the Dark Side of Smart Lights” The Protective Effect of Smart City Infrastructures

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Abstract

In this paper, we investigate the protective effect of smart street lighting on public safety. Smart lights have a variety of features, such as video surveillance or gun-shot detection. Some of these features can have a deterrent effect on crime. Other features, however, such as adaptive brightness control, may also encourage crime. Using a comprehensive dataset on the crimes committed in downtown San Diego (CA) during 1st May 2017 and 30th April 2018, we investigate the crime rates a priori and posterior to the installation of smart lights in this area. The results of the empirical analysis suggest that smart lights have a statistically significant negative impact on crime and that their installation increases the safety of citizens.

1. Introduction

The “smart city” concept counteracts problems arising with rapid urbanization, and population growth in metropolitan areas [e.g., 1], which highlights the importance of Information and Communication Technologies (ICT) to encompass modern urban production factors in a common framework [2]. ICT is an enabling technology in smart cities [3], to provide more efficient public information and services to allow a smarter urban life [1, 4]. In smart city concepts, “smart lights” play a crucial role in many cases, by acting as an enabler in the context of the Internet-of-things (IoT) [5]. Smart lights have a broad variety of capabilities. On the one hand, they communicate with other sensors and act as a node or gateway in a sensor network on the IoT level [6, 7].

On the other hand, smart lights can have own sensors and processing capabilities. These are mainly sensors that measure environmental factors (e.g., air temperature, humidity, air pollution, vibration, light intensity) or are used for public monitoring and surveillance (e.g., microphones, cameras) [8]. Equipped with processing and communication capabilities, smart lights can both, process data locally and offload sensor data to some gateway or sensor network. This unique capability enables a wide range of applications, especially in the surveillance and public security area. For example, built-in microphones can detect shots by processing acoustic signals and communicate this information to neighboring smart lights. The information exchange allows an exact localization of the shooting – including an automatic report to the nearest police station [8, 9]. Smart lights have even more features. For instance, they can adjust their light intensity to the current daylight, the weather conditions and the presence of people in the surrounding area, and can thus reduce energy costs [10]. Further, they can also communicate their current status and initiate service requests, which also reduces maintenance costs.

Previous research analyzed smart lights in various academic disciplines but focused mostly on technology-related questions, such as how to implement and integrate smart lights in a smart city and an IoT ecosystem [e.g., 7, 10, 11]. Commensurately, the scientific verification of the advantages of smart lights for society, including the impact of smart lights on crime, remains scarce. This is very surprising, as the goal of the deployment of smart lights is usually related to a range of expected improvements such as environmental friendly and low energy infrastructure, cost reductions via predictive maintenance, cost reductions via increased energy efficiency, increased public safety due to features such as Closed Circuit Television (CCTV) or automatic recognition of gunshots via microphones [8, 9]. Meanwhile, energy efficiency and other key performance indicators are easy to measure and assess, the smart light’s impact on public safety remains a challenge which needs evaluation using empirically founded studies.

Because to date, and to the best of our knowledge, no empirical studies are assessing the effect of smart

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lights on crime, we address this gap in research and analyze the effect of the introduction of smart lights in the downtown area of San Diego, between the 1st May 2017 and 30th April 2018, empirically.

The remainder of this paper is structured as follows: The next sections discuss relevant related work, the collected data, as well as our empirical approach through which we wish to identify the effect of smart lights on crime. Then, we present our findings and discuss potential implications for relevant decision-makers, the study's main limitations and paths for future research.

2. Related Work

2.1. Street lights and crime

Due to the high costs incurred by criminal behavior on the individual and societal level, it is natural that policymakers and jurisdiction enforcers alike intent to prevent crime through a variety of countermeasures [12]. One of the most common public precautions studied in relation to crime deterrence is the deployment of improved or strategically located street lights [13-15]. Accordingly, there is a vast number of studies assessing the effect of traditional street lights on crime rates within several areas and during various times of the day. However, existing studies present somewhat inconclusive results. Some studies, for instance, find that improved lighting had little or no effect on crime [e.g., 16, 17], others find that improved and strategically deployed illumination can reduce crime substantially [e.g., 15, 18], and again others argue that improved street lighting can reduce property crimes but do not alter the occurrence of violent crimes [19].

Xu and colleagues [15], for instance, analyzed the spatial association of street light density, neighborhood social disorganization characteristics, and crime in Detroit, and found evidence for an inverse effect of street light density and crime rates. Similarly, studies performed by Painter and colleagues [18, 20] within the framework of several projects across the UK, also present evidence for a deterrent effect of improved street lighting on crime. Also, Painter and colleagues discuss the mechanism through which street lighting can deter crimes. They explain that street lighting acts as a deterrent for crime because they increase the chances that more people are using the streets during the dark so that offenders face higher probabilities of being observed and apprehended [14, 18-20]. Because crime is a covert activity, the protective power of street lights lies in their potential to increase the offenders' perceived risk of being caught [16].

In contrast to the scholars who presented evidence for a link between improved street lights and crime, other academics found little or no effect of street lights on crime rates in general. Thus, these scholars sustain that the deployment of streetlights does not necessarily deter crime, but on the contrary, under certain circumstances, it can even induce the exact opposite effect [16, 17]. According to these scholars, the installation of improved smart lighting can benefit criminal activities via several channels: Firstly, improved lighting can attract more people outside and to the streets and thus bring more potential victims with more offenders together and benefit violent crimes [19]. Second, once potential offenders and victims are both out on the street, improved street lighting enables criminals to assess their victims better regarding vulnerability and attractiveness [19], meanwhile giving potential victims a false sense of security which in turn makes them less vigilant than otherwise [19]. Third, if more people are outside, on the streets, more houses are left without guardianship, so that improved street lighting could foster property related felonies [19].

Despite the inconclusive results presented by the existing literature and numerous discussions about the mechanisms through which improved street lighting could affect crime levels in general, academics agree that improved lighting is neither a measure to stop crime entirely nor a physical barrier for crime. They agree that street lightning is rather an alteration of the environment, which, under certain circumstances, can potentially alter the offenders' opportunities and perceived risks and lead them to the decision to refrain from illegal activities [21]. Hence, it stands to reason that improved and strategically savvy deployed lighting alone is not enough to prevent all types of crimes in all types of situations. As Pease [21] argues "no public place, however well lit, will be crime free if offenders have good reason to believe that they will not be recognized, or, if recognized, will not be reported to the police" [21]. Against this backdrop, effective crime prevention measures should look at combining street lights with other types of crime deterrence precautions. One popular modus operandi is to combine street lights with other surveillance technologies, such as CCTV.

2.2. CCTV and crime

Besides other types of surveillance activities pursued by law enforcement and other public employees (e.g., bus drivers, parking attendants), CCTV is yet another widely spread and popular situational approach to crime prevention [22, 23]. Employed not only by private individuals but also by law enforcement officials [22] alike, CCTV is expected to deter crime (analogous to improved street lighting) by reducing opportunities for crime and increase offenders' perceived risk of being caught and punished. In theory, and in particular as postulated by the Deterrence or Rational Choice Theory, crimes are the outcome of the offenders' rational decision on the trade-off between expected gains and the perceived risks of being caught [24].

Previous empirical research on CCTV's impact on crime presents ambiguous results. Some studies support that CCTV can deter crime only partially. Other studies suggest that there is no effect of CCTV on crime. Yet again other studies present evidence for some deterring effect of CCTV on at least certain types of crimes [e.g., 22, 23, 25, 26]. Priks for instance [23] studied the influence of CCTV on crime in several subway station in Stockholm and concluded that CCTV can deter crimes, especially in the busier railway stations. Similarly, Caplan and colleagues [22], found that after installing police-monitored CCTV the number of shootings and auto thefts decreased. Meanwhile Brown [25] ascertained that CCTV deters only property crime, and especially burglaries. In contrast to Brown, La Vigne and colleagues [26] studied various implementation sites across the U.S. and presented evidence that CCTV's has the potential to deter both – violent and property crimes, yet not in all locations and under all implementation strategies (i.e. continuous surveillance performed by designated personnel, or access to CCTV for all law enforcement members).

The finding that the efficiency of CCTV depends heavily on the implementation strategy and location of the CCTV installation is in line with the findings of other studies which focused more on the cost-efficiency of CCTV and street lighting as crime deterrence instruments. Lawson and colleagues [27] for instance, assessed the cost-effectiveness of both, CCTV and street lighting, on crime and found that improved street lighting is in most cases more cost-effective than CCTV, except within the context of crime hot spots, where CCTV is the better and more cost-effective method to reduce crime [27].

Given the inconclusiveness of the existing empirical results supporting CCTV's potential to deter crime, it is surprising that many cities, counties, regions and even countries (i.e., the UK) choose to implement CCTV as a preventive measure against crime. Besides the discussion on the cost-effectiveness of CCTV versus improved street lighting, there is also an ongoing debate on the intrusive use and misuse of CCTV in general [28].

2.3. Smart lights and crime

Due to their importance in the context of Smart Cities [5], previous research analyzed smart lights in various academic disciplines. The majority of studies that examine smart lights, typically focus on technology and questions how to technically implement and integrate smart lights in the context of a smart city and the corresponding IoT ecosystem [e.g., 7, 10, 11]. An empiric investigation on the effect of smart lights on crime is however still missing. A potential reason for the missing empiric research on this topic is that unlike factors that are quite straightforward to measure and verify (i.e., energy consumption, maintenance costs), the smart lights' effect on public safety presents a challenge which requires a quasi-experimental setting within the real world.

Overall, due to the technical capabilities of smart lights (i.e., CCTV, microphones, adaptive brightness control), we would be inclined to expect a deterring effect of the introduction of smart lights on crimes. Nevertheless, if taking into consideration that adaptive control of brightness based on light conditions and movement of cars and pedestrians, it is also conceivable that the installation of smart lights might benefit the occurrence of crime.

The primary goal of the adaptive brightness control is to contribute to more sustainable energy consumption by not consuming energy when not needed [29]. Though legitimate from an environmental point of view, the adaptive brightness control feature might come at the cost of public safety. In practice, the adaptive brightness control enables the smart lights to create a "wave of light" when necessary – i.e., when individuals or vehicles approach. This depicts a serious risk, as it enables offenders to hide in the dark and lurk potential victims from a safe, not illuminated location. Also, because potential victims might not have fully lit view over an area (e.g., a street, a park), they might feel less secure and ultimately avoid such locations. If more people avoid such locations, the people who do visit those locations are more prone to crime because less frequented locations have less potential witnesses who might observe and help apprehend criminals [20]. Due to the inverse relationship between public street usage and crime (i.e., sparse usage of a public space is related to lower number of potential witnesses and a reduced perceived risk of being caught), potential offenders might find the adaptively controlled smart lights as appealing places to commit felonies [20].

Given that manufacturers of smart lights are actually promoting smart lights as safety-enhancing products [e.g., 8] and that smart lights are becoming more important in the infrastructure of cities that want to become more intelligent, it is essential to be able to correctly predict the impact and spill-over effects of smart lights on public safety.

3. Data and Empirical Model

3.1. Data sources

For this study, we collected the information on crimes (i.e., crime type, location and time the crime was committed) via crawlers from one of the most comprehensive websites to map and visualize crimes in the U.S. (i.e., www.crimemapping.com). Altogether we crawled 15 crime categories, which add up to the total number crimes committed in the area and period of interest (i.e., San Diego downtown, from the 1st of May 2017 to the 30th of April 2018). Below, a listing of the crime categories crawled (in alphabetical order) and their share of the total amount of crimes in parenthesis:

Arson - Willful, malicious burning of a structure, vehicle, or personal property. (0%)

Assault - Attack on a person to commit injury. Aggravated assault usually includes a deadly weapon. Domestic violence is not included. (52%)

Burglary - Unlawful entry of a structure to commit a theft or other felony. (1%)

Disturbing the Peace - Any behavior that tends to disturb the public peace. (0%)

Drugs / Alcohol Violations: - Drug abuse or liquor laws violations. (22%)

DUI - Driving or operating a vehicle while under the influence of alcohol or narcotics. (2%)

Fraud - Deception intended to result in financial or personal gain. (1%)

Homicide - Unlawful killing of one person by another. (0%)

Motor Vehicle Theft - Theft of a car, truck, motorcycle, or any motor vehicle. (2%)

Robbery - Taking property from a person by force, threat of force, or fear. (3%)

Sex Crimes - Rape, prostitution (2%)

Theft / Larceny - Unlawful taking of property from another person. Embezzlement, forgery, check fraud, and theft from a vehicle are excluded. (9%)

Vandalism - Willful, malicious destruction, damage, or defacement of property. (5%)

Vehicle Break-In - Theft of articles from a vehicle. (2%)

Weapons - Violation of laws prohibiting the manufacture, sale, purchase, transportation, possession or use of deadly weapons. (1%)

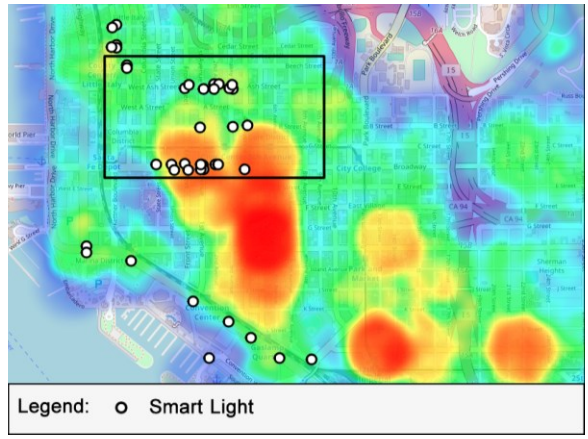

Figure 1. Smart lights with a heat map reflecting the crimes in San Diego downtown

Figure 1 shows the distribution of crimes and smart lights across San Diego.

Table 1. Overview number of crimes by crime type and day/night distribution

Crime Type	Day	Night
Arson	0	2
Assault	365	265
Burglary	5	4
Disturbance	0	0
Drugs	152	110
DUI	0	19
Fraud	6	4
Homicide	0	0
Motor Vehicle Theft	15	15
Robbery	13	18
Sex Crimes	10	11
Theft	55	50
Vandalism	26	29
Vehicle Break-in	6	18
Weapons	6	6
Total	659	551

To disentangle the effect of the various features of the smart lights on crime (i.e., audio and video surveillance versus the adaptive light control), we distinguish between crimes committed during the night and day. The Table 1 provides an overview of the types and number of crimes committed during the period of interest. To determine the number of crimes committed during the day and the number of crimes committed at night, we use the sunset and sunrise times of a day to decide for each crime to which group it appertains (i.e., crimes committed during the day or night). Because in reality, the times of sunrise and sunset vary on a daily basis each crime has been classified individually and by the varying daily time of sunrise and sunset. As the table shows, most crimes happen during the day rather than at night, contradicting the common expectation that most crimes occur at night. In our sample, the night-time seems to be more popular only for robberies and vehicle break-ins.

In addition to the crime data, we also acquired data about the weather conditions from the U.S. Department of National Oceanic and Atmospheric Administration (NOAA) and information on public holidays from the website of the City of San Diego. The Environmental Services Department of the City of San Diego provided information about smart lights (e.g., location, technical specifications, and installment date).

3.2. Empirical model

To identify the effect of smart lights on crime, we exploit the fact that smart lights have been installed only in certain designated street corners in San Diego downtown area. Because the remainder of the street corners in the San Diego downtown area are still regular streetlights, we employ the Differences in Differences (DiD) technique where the installation date of the lights (i.e., the 1st of November 2017) is the starting date of the treatment and the street corners with smart lights appertain to the treatment group.

To be more specific, we estimate the following model specification on several datasets, with various granularities of crime data.

$$DV_{it} = \alpha_i + \delta_{it} * \sum_{j=0}^{k} \beta_{jt} * time\ related\ effects_k + \sum_{m=0}^{n} \gamma_m * \ weather_{\ m} + \delta_{it} * period + \theta_{it} * treatment + \delta_{it} * DID + \varepsilon_{it} \tag{1}$$

with

DV: total number of crimes on a daily basis or during the night or daytime, or total number of crimes of a certain crime type.

i: street corner identifier (i.e. 1,2,3,4…).

t: time indicator (daily data).

time related effects: trend, effect of day of the week, public holidays, or public events.

weather: average temperature, square of average temperature and rain in mm. We expect that the effect of temperature follows the form of a quadratic function, rather than a linear function.

period: dummy variable which takes value 1 as soon as the smart lights have been installed (i.e. 1st of November 2017).

treatment: dummy variable which takes value 1 if there the street corner has at least one smart installed.

DID: interaction term (= period*treatment) measuring the effect of the treatment (i.e. installation of smart lights) on crimes.

Our estimation model is built on the insights presented by previous research on the main environmental determinants of crime. Accordingly, it controls for weather conditions [e.g., 30, 31, 32], time-related effects (e.g. day of the week [e.g., 33, 34-36]), as well as public holidays [e.g., 36]. Weather conditions, day of the week, time of the day or public holidays are according to the literature determinants of crime because they motivate people to change their routines, and spend more time outside. This behavior can increase the number of crimes through following channels [e.g., 30, 31-33, 36]: Firstly, people leave their dwellings longer without guardianship during sunny days, public holidays or on weekends, so that more property crimes are likely to occur. Second, because more people are outside, the chances that offenders meet potential victims is higher than usual, and thus the likelihood for violence-related crimes (e.g., assault) increases.

In addition to the environmental determinants of crime, our model also distinguishes between crimes committed during the day or night. Due to the adaptive lighting capabilities of the smart lights and the increased level of surveillance they provide via their microphones and cameras, it is very likely that the effect of smart lights might be different during the day than during the night. In line with this expectation and following the call of previous studies [15, 19], we estimate all our models by looking not only at the number of total crimes per day and crime type before and after the introduction of smart lights but also at the number of crimes during the day and night by controlling for street corners which are adjacent and non-adjacent to the treated corners [15].

In addition, as suggested by previous work studying the effect of improved street lighting and CCTV on crime, we also distinguish between property and violence crime, whereby the number of property crimes in a day equals the sum of all burglaries, motor vehicle thefts, vandalism cases, vehicle break-ins and theft felonies which occurred during a day, in a particular street corner. Similarly, the number of violent crimes consist of the sum of assaults, homicides, robberies and sex crimes registered on a particular day for a specific corner.

Finally, as our data on crime is available as count data which is zero-inflated and overdispersed, we estimate the empirical model presented above via a negative binomial regression using STATA. For a better interpretation of the estimation results, we report the results of all estimations as incidence rates.

Figure 2 provides an overview of the street corners analyzed in this study.

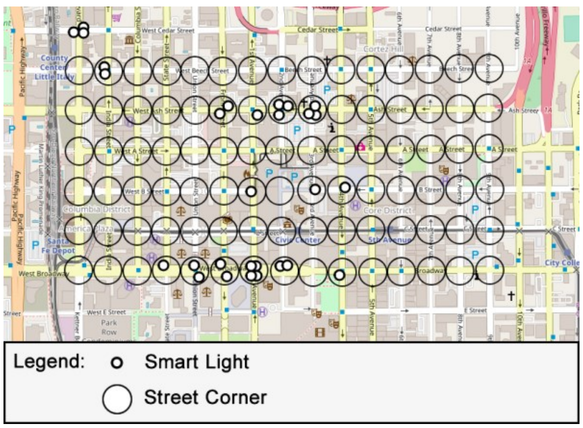

Figure 2. Overview of the street corners analyzed

4. Findings

4.1. Impact of smart lights on the total number of crimes

Table 2 lists the results of the estimated model for the aggregated number of crimes per day and per corner. As the estimation results show (Table 2, Col. (1)) the introduction of smart lights in the downtown area of San Diego decreases c.p. the number of total crimes by approximately 37% (DID=0.629 with $p<.05$). This decrease in the total number of crimes after the introduction of smart lights seems to be driven by a decrease in the number of crimes committed during the night time. As Table 2, Col. (1a) suggests, the introduction of smart lights had no statistically significant impact on the aggregate number of crimes committed during the day but a statistically significant ($p<.1$) impact on the aggregated number of crimes committed during night time. These results are to some extent surprising, as they match the expectations formulated in section 2.3 only partially. Related to potential effects of CCTV and surveillance on crime, it is noteworthy that none of the treatment-related coefficients (e.g., Period, Treatment, DID) estimated for the aggregated number of crimes which took place during the day, are statistically significant. Hence, we note that the results of our analysis do not support the existence of a deterring effect of CCTV on the total number of crimes or the aggregated number of property or violent crimes (see Table 2, Col. (2b) & (3b)).

4.2. Impact of smart lights on individual types of crime

As stated in section 2.3, we expected that the adaptive brightness control of the smart lights deployed in San Diego would rather promote than deter crimes by decreasing the public usage of certain areas. This expectation did not materialize. In fact, as Table 2 Col. (1b) reveals the introduction of smart lights decreases c.p. the number of total crimes committed during nighttime by 45%. In contrast, when looking at the group of violent and propriety related crimes separate from one another, the results of our analysis does not yield statistically significant incidence rates.

Further, as the results of the analyses of the effect of smart lights on individual types of crime suggest (Table 3), the introduction of smart lights in the downtown area of San Diego decreases c.p. the aggregated number of assaults per day by approximately 60% (Table 3 Col.(1)) ($p<.01$). Similarly, it decreases the number of assaults conducted during daytime by 53% ($p<.1$) and the number of assaults conducted during nighttime by 66% ($p<.1$). In addition, the estimation results show that the introduction of smart lights decrease the drug-related offenses c.p. on aggregate by 77% ($p<.01$), the drug-related crimes during the day by 73% ($p<.01$) and drug-related crimes committed during the night by approximately 68% ($p<01$).

Although these results are unexpected, they are plausible and corroborate the notion that overall, the introduction of smart lights can benefit public safety not only during the day – i.e., via CCTV and microphone surveillance but also at night.

In general, previous research on the impact of improved street lighting on crime has been conducted under the prevalent premise that at night, a good and clear view of the environment can have a protective function for potential victims. Accordingly, previous research assessed the impact of improved street lighting on crime based on projects and ideas which tried to ensure that the areas assessed were either lit-up brightly or constantly. Now, the premise underlying previous research is challenged by empirical evidence that smart lights with adaptive brightness control (i.e., lights which do not light up the entire environment simultaneously and at all times, but rather based on movement sensors), can have a substantial deterrent effect on certain types of crimes during both- day- and nighttime.

5. Discussion

The goal of this study was to assess empirically if smart lights have a deterrent effect on crime by analyzing the crime rates in San Diego prior and posterior to the introduction of smart lights.

Based on the main findings of this study and against the prevalent notion that effective preventive

Table 2. Estimation results aggregated number of crimes

VARIABLES	(1) Total crimes	(1a) Total crimes (day)	(1b) Total crimes (night)	(2a) Violence crimes (day)	(2b) Violence crimes (night)	(3a) Property crimes (day)	(3b) Property crimes (night)
Period (=1 after installation of smart lights)	1.1085 (0.1530)	0.99999 (0.2220)	1.2995 (0.2280)	1.0003 (0.2600)	1.2662 (0.2880)	0.9181 (0.4120)	1.3965 (0.3720)
Treatment (=0 if corner is in control group)	0.8369 (0.4400)	0.8755 (0.4880)	0.6970 (0.4840)	0.6029 (0.6830)	0.4561 (0.7200)	1.5667 (0.3760)	1.0981 (0.4800)
DID (treatment effect)	0.6294** (0.1990)	0.8171 (0.2640)	0.5505* (0.3230)	0.5488 (0.4010)	0.5886 (0.4240)	1.3580 (0.3760)	0.4946 (0.5010)
Trend	0.9991 (0.0006)	0.9965*** (0.0009)	1.0017* (0.0009)	0.9966*** (0.0010)	1.0014 (0.0011)	0.9964** (0.0015)	1.0021 (0.0014)
Rain in mm	1.3854 (0.2710)	0.3506 (0.7770)	2.4013*** (0.3110)	0.4308 (0.7950)	2.7020*** (0.3520)	0.0736 (2.8340)	1.9232 (0.6020)
Temperature	0.9952 (0.0951)	0.8082 (0.1320)	1.1331 (0.1480)	0.8122 (0.1550)	1.0526 (0.1830)	0.8163 (0.2450)	1.2789 (0.2520)
Temperature^2	1.00005 (0.0007)	1.0016 (0.0010)	0.9991 (0.0011)	1.0015 (0.0012)	0.9997 (0.0014)	1.0016 (0.0018)	0.9982 (0.0019)
Weekday[b] (Mon)	1.1853 (0.1180)	1.1047 (0.1670)	1.2461 (0.1720)	0.9992 (0.1980)	1.2662 (0.2170)	1.3703 (0.3030)	1.2177 (0.2800)
Weekday[b] (Tue)	1.0997 (0.1170)	1.3073* (0.1590)	0.8253 (0.1880)	1.2982 (0.1840)	0.8985 (0.2310)	1.2840 (0.3040)	0.6900 (0.3220)
Weekday[b] (Wed)	1.1275 (0.1170)	1.1595 (0.1630)	1.0498 (0.1760)	1.1865 (0.1870)	1.0370 (0.2230)	1.0560 (0.3170)	1.0420 (0.2860)
Weekday[b] (Thu)	1.1219 (0.1170)	1.1712 (0.1630)	1.0338 (0.1770)	1.1996 (0.1870)	1.1320 (0.2180)	1.0850 (0.3160)	0.8967 (0.2950)
Weekday[b] (Fri)	1.1936 (0.1160)	1.2105 (0.1630)	1.1630 (0.1730)	1.0422 (0.1950)	1.1009 (0.2220)	1.6291* (0.2900)	1.2251 (0.2780)
Weekday[b] (Sat)	1.0873 (0.1180)	1.1025 (0.1660)	1.0705 (0.1750)	0.9516 (0.1980)	0.9506 (0.2270)	1.4859 (0.2970)	1.2473 (0.2750)
Public Holidays[b]	0.9970 (0.1770)	0.9714 (0.2560)	1.0322 (0.2530)	1.0817 (0.2940)	0.9119 (0.3400)	0.7175 (0.5190)	1.2226 (0.3820)
Constant	321.8225 (16.2000)	44801.6389** (4.9020)	0.0162 (4.9200)	8.0794×10^8 (362.0000)	0.2332 (6.0730)	753.7042 (8.4740)	0.00003 (8.2920)
Observations	34,500	34,500	34,500	34,500	34,500	34,500	34,500
Num. Corners	92	92	92	92	92	92	92

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

crime measures entail either improved lighting projects or CCTV surveillance [e.g., 27], we postulate that a combination we postulate that a combination of the two prevention measures in the form of smart lights will yield the best results not only in terms of public security but also probably in terms of cost-efficiency.

Although this study did not dispose of the data necessary to perform a cost-effectiveness comparison between smart lights and common street lighting, we expect that the investments for the smart lights introduction will pay off quickly due to their the direct and indirect savings they incur.

In 2017, San Diego county's expenditure on incarcerations and crime responses (e.g., attorney prosecution, public defenders, juries and other court-related costs) amounted $758.1 million dollars (i.e., 18.3% of the total county budget) [37]. Assuming that on average the 37% drop in crimes in San Diego downtown is representative for most of San Diego's

Table 3. Estimation results of selected crime types at day and night

VARIABLES	(1) Assault	(1a) Assault (day)	(1b) Assault (night)	(3) Drug	(2a) Drug (day)	(2b) Drug (night)
Period (=1 after installation of smart lights)	0.9868	1.0038	1.0183	1.2866	1.8294	0.8114
	(-0.1970)	(-0.2670)	(-0.3110)	(-0.3040)	(-0.4120)	(-0.4630)
Treatment (=0 if corner is in control group)	0.5488	0.5706	0.4115	7.4113***	7.4410***	3.4522***
	(-0.6720)	(-0.7380)	(-0.7930)	(-0.3780)	(-0.4430)	(-0.4510)
DID (treatment effect)	0.3953***	0.4743*	0.3434*	0.2341***	0.2621***	0.3243**
	(-0.3470)	(-0.4450)	(-0.5700)	(-0.2690)	(-0.3440)	(-0.4520)
Trend	0.9991	0.9968***	1.0022*	1.0012	0.9979	1.0052***
	(-0.0008)	(-0.0010)	(-0.0012)	(-0.0011)	(-0.0015)	(-0.0017)
Rain in mm	1.6112	0.4593	3.0283***	0.2786	0.5257	0.0355
	(-0.3050)	(-0.8000)	(-0.3510)	(-1.3690)	(-1.3380)	(-3.1270)
Temperature	0.9316	0.8470	0.9267	1.0606	1.0782	0.9971
	(-0.1190)	(-0.1620)	(-0.1850)	(-0.1820)	(-0.2570)	(-0.2620)
Temperature^2	1.0005	1.0011	1.0006	0.9996	0.9995	0.99998
	(-0.0009)	(-0.0012)	(-0.0014)	(-0.0014)	(-0.0019)	(-0.0020)
Weekday[b] (Mon)	1.0994	0.9572	1.2473	2.1598***	2.1749**	2.1022*
	(-0.1490)	(-0.2040)	(-0.2290)	(-0.2670)	(-0.3370)	(-0.4370)
Weekday[b] (Tue)	1.1085	1.2599	0.8659	2.2457***	2.2255**	2.3048**
	(-0.1460)	(-0.1890)	(-0.2440)	(-0.2640)	(-0.3320)	(-0.4250)
Weekday[b] (Wed)	1.1480	1.1984	1.0188	2.7732***	2.2979**	3.4799***
	(-0.1450)	(-0.1910)	(-0.2360)	(-0.2540)	(-0.3290)	(-0.4010)
Weekday[b] (Thu)	1.1185	1.1712	1.0150	2.1255***	2.0959**	2.1043*
	(-0.1460)	(-0.1920)	(-0.2360)	(-0.2640)	(-0.3340)	(-0.4290)
Weekday[b] (Fri)	1.0140	0.9694	1.0537	2.2012***	2.3679***	2.0585*
	(-0.1510)	(-0.2020)	(-0.2360)	(-0.2640)	(-0.3290)	(-0.4340)
Weekday[b] (Sat)	0.9344	0.9312	0.9447	1.4405	0.4484	3.1614***
	(-0.1530)	(-0.2030)	(-0.2390)	(-0.2850)	(-0.4930)	(-0.4090)
Public Holidays[b]	0.9954	0.9984	1.0175	0.5957	0.6294	0.5337
	(-0.2310)	(-0.3180)	(-0.3440)	(-0.4230)	(-0.5180)	(-0.7320)
Constant	2.7234×10^7***	2.2463×10^8	18.8215	0.0076	0.0133	0.0085
	(-3.9870)	(-395.1000)	(-6.1330)	(-6.1420)	(-8.7420)	(-8.6530)
Observations	34,500	34,500	34,500	34,500	34,500	34,500
Num. Corners	92	92	92	92	92	92

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

districts, the installation of smart lights could help the county decrease their spending on incarceration and crime response by approximately 6.7% (computed based on [37]). This saving potential shows the smart lights' capability to save public funds, which can then be reallocated to address other pressing issues in the county.

However, the investments related to the installation of smart lights is likely not amortized only by cost reductions related to energy savings, savings in policing resources, or savings in crime-related treatment costs but also by other indirect benefits gained from an increase in the actual and perceived safety. For example, San Diego's housing market can benefit from a decrease in crime rates. Since a decline in crime can make previously dangerous districts attractive again, the city's housing supply can be expanded and housing shortages in other areas can be alleviated. The city can also benefit from a better quality of life [38], which in turn fosters the city's (economic) growth [4, 39].

Altogether, this study reveals the impact of smart lights on crimes and ultimately society. Given that governments are striving to improve the livelihoods of their citizens, by making cities smarter and safer decision-makers require a solid decision-making basis which can allow them to decide which crime deterrence mechanisms should be implemented when and where in a city, county or state. Due to the scarcity of such studies, we invite fellow researchers to pursue this question further.

Also, we invite fellow researchers to conduct studies which address this study's main limitations and verify the validity of the results presented in this paper, by replicating this study in a longer term and for other locations. Because the smart lights of San Diego downtown went live only on the 1st of November of 2017, our study comprises only data from six months before and six months after the treatment begun. Previous studies suggest that the effect of deterrent measures such as improved lighting and CCTV monitoring could only be effective in the short term. Therefore, further long-term studies on this topic are needed to ensure that intelligent luminaires have the potential to be effective against crime in the long term. Related to our study's limitation that our area of analysis is solely the downtown part of San Diego, whereas most of the crimes might occur in the suburbs of the city, we also invite fellow researchers to replicate this study with data comprising several suburbs of San Diego, or several cities across the US.

If further studies corroborate our findings (i.e., that smart lights can decrease crime rates in the long run, and in all types of neighborhoods and cities), smart lights are likely to establish as crime reduction measure. In this case, because smart lights have not only advantages but also disadvantages, it is essential that decision-makers bear in mind that the introduction of smart lights is an element that improves but does not replace the work of police personnel.

The smart lights' numerous sensors and cameras, for instance, constantly gather data about the pulse of a city and its citizens. As the data gathered is stored and processed centrally, smart lights can also pose a threat to society. Hence, it is essential that decision-makers ensure that the cities and counties introducing smart lights into their environment have the necessary governance structure in place to operate and maintain the smart lights seamlessly and to securely store and process the data gathered. Only if decision-makers succeed to build a suitable governance structure which ensures that the benefits outweigh the potential drawbacks of smart lights, such technologies can be considered as a useful tool for crime deterrence.

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